Int. J. Econ. Environ. Geol. Vol.15 (4) 33-48, 2024
Journal home page: www.econ-environ-geol.org

Open Access
ISSN (Online) 2223-957X

A Framework for Measuring the Sustainability of Energy Systems: A Comparative Analysis of Pakistan, European Union and USA

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Received: *10 November, 2024* ***Accepted:*** *26 December, 2024*

Abstract: Sustainable energy infrastructure relies on the adoption of advanced low carbon and affordable technologies. In developing countries like Pakistan, sustainability of the energy system has become a challenge because of the gap between electricity demand and supply, inefficient energy generation, dependence on carbon-intensive technologies, low electrification rate and increased effects of climate change. Measuring the sustainability of energy systems is vital to ascertain the level of sustainability, innovativeness and the reliability. Various studies have proposed indices for measuring the sustainability of energy systems. Rarely can any index boast of providing a comprehensive framework for measuring all aspects of sustainability. This study has reviewed the existing indices and developed a framework based on strengths and weaknesses of the existing indices. The framework has divided the sustainability into four main segments with further division into thirteen sub-segments which consist of forty-nine indicators. Later, we have applied the newly proposed framework to comparatively measure the sustainability level of energy system in Pakistan, USA and European Union. The results provide a vital input to the policy makers to focus on critical areas for enhancing the sustainability of energy systems in developing countries.

Keywords: Energy systems, national energy policy, sustainability assessment framework.

Introduction

As energy plays a vital role in economic growth and improving living standards, a shift from expensive and environmentally hazardous conventional energy resources and technologies towards the clean and renewable energy resources and technologies is imminent to ensure global sustainable development (UN, 2018). Alongside a surge in the reliance of human beings on energy, the difficulties in producing affordable and sustainable energy are also increasing. Energy sustainability has become a challenging task for the whole world, whether it is developed world or the developing countries (Mainali et al., 2014). Sustainable energy infrastructure can be defined as an energy system which can utilize energy resources to meet present needs without compromising needs of the future generations (Glavič and Lukman, 2007).

One of the major global challenges is to keep pace with the increasing energy demand. On one side, approximately 1 billion people have no access to electricity, while on the other hand, around 2.8 billion people are dependent on primary energy resources such as coal, wood, charcoal etc. for meeting their energy needs (Office, 2016). With increasing energy demand, the use of fossil fuels which is mostly depended on, has become unsustainable due to its environmental hazards, depleting resources, and fluctuating prices.

Supply of modern, accessible, affordable and reliable energy has become a cornerstone to economic development, environmental protection, social progress, poverty reduction, equity and improving living standards (Chu and Majumdar, 2012). Energy sustainability is progressively becoming a goal which is aspired by many countries around the globe (Hussain et al., 2021; Ali et al., 2021). According to Oyedepo (2012); Vidadilli et al. (2017) main challenge to energy sustainability is achieving balance in all the dimensions of sustainability i.e. social, environmental, economic and technology. Ozturk and Yuksel (2016) have indicated key targets for the sustainable energy system, including zero emissions of CO_2, no important ecological harmful impacts, improving security of the energy transition, decreasing the cost of energy production and improving the use of green technologies.

Evaluating an energy system against all important aspects of sustainability is quite challenging. Many studies have suggested frameworks and indices to evaluate the sustainability of energy systems. The frameworks and indices such as Sustainable Energy Development Index (Iddrisu and Bhattacharyya, 2015), The Energy Development Index (IEA, 2018c), Energy Sustainability Indicators (OLADE et al., 2000), Energy Indicators for Sustainable Development (IAEA, 2005) have helped in evaluating energy systems by using different indicators of sustainability appendix. Despite the excess of literature on energy sustainability, only a few indices/frameworks are widely recognized. Most of the indices/frameworks either do not provide a clear picture of sustainability or capture only a few aspects of it. Additionally, these indices lack integrated approach and are not applicable to all the energy systems and countries as their focus is mostly on a single system in a country (Emodi and Boo, 2015; Neves and Leal, 2010; Chu and Majumdar, 2012; Goldemberg, 2007; Evans et al., 2009).

This paper proposes a framework for evaluating the sustainability of energy systems by building on the strengths and weaknesses of previous efforts and to overcome the prevalent shortcomings in existing literature. Most of the existing indicators are designed for specific cities or countries, lack quantification, and too comprehensive or do not address all dimensions of sustainability. This paper uses four main segments, namely economic, social, environmental and technological with further division into thirteen sub-segments and forty-nine indicators to evaluate the sustainability of energy systems. Case study of a developing country, Pakistan is used to validate the proposed framework in comparison with European Union and USA. This will provide significant input to policy makers for devising policies to promote development of sustainable energy systems.

Review of Existing Indices and Frameworks for Measuring Sustainable Energy Systems

Most common energy specific indices include the energy development index, energy sustainability indicators, the energy indicators for sustainable development, energy architecture performance index, the multidimensional energy poverty index, sustainable energy development index and energy trilemma index. These indices are further discussed below.

The Energy Development Index (EDI)

The main motive behind the development of energy development index by (IEA, 2018c) was to follow the improvements made by a country in transitioning from the use of solid fuels to modern energy services (Johansson et al., 2012). EDI is measured by factoring in UNDP's Human development index. It is multi-dimensional index including three dimensions and four indicators. The strengths and weaknesses of this index are shown in Appendix Table A-1.

Energy Sustainability Indicators (ESI)

This study was carried out by OLADE et al. (2000) to target energy sustainability in the Latin American and Caribbean countries. A set of eight indicators with same weightage were included in this study. It aimed to provide recommendations to the policymakers to develop a sustainable energy policy. Appendix Table A-2 gives an overview of the strengths and weaknesses of this index.

The Energy Indicator for Sustainable Development (EISD)

It includes three dimensions which are further divided into seven themes, nineteen subthemes and thirty indicators. These set of indicators were designed to provide assistance to policy makers by providing deep understanding and information on current energy trends (IAEA, 2005). EISD is very popular among policymakers to measure the sustainability of energy sector, but it is very difficult to do comparisons between two countries using these indicators because of high data requirements. Some of the EISD indicators could easily distinguish between good and bad measures e.g. reducing air pollution or providing clean energy. While some indicators are not designed to clearly distinguish between desirable and undesirable conditions like energy use per capita of a country could be low because of energy poverty or due to energy conservation and highly efficient energy system. Some indicators could indicate negative development in one dimension but could have positive impacts in other dimensions. For example, the use of kerosene oil in a developing country could save time and reduce indoor pollution while it also increases the total percentage of income spent on energy by a family. Appendix Table A-3 gives an overview of the strengths and weaknesses of this index.

Energy Architecture Performance Index (EAPI)

Energy architecture performance index is developed by world economic forum in collaboration with Accenture (WEF, 2017). This indicator currently ranks 127 countries based on energy access and security, environmental sustainability and economic growth. All the 18 indicators used in this tool are given different weightage. The first edition of index from Global Energy Architecture Performance

Report 2013 are used to build this tool (Shortall and Davidsdottir, 2017). This tool has five years of data which can be used to find the progress of a country in these years. Appendix Table A-4 gives an overview of the strengths and weaknesses of this index.

Multi-dimensional Energy Poverty Index (MEPI)

This tool was developed by Nussbaumer et al. (2012) to measure only one aspect of the sustainability i.e. affordable energy access or energy poverty. A multi-dimensional approach is used by this tool to capture all the aspects of energy poverty. The focus of this tool is to identify the quality of energy services provided to consumers. This framework consists of five dimensions and six indicators as shown in Appendix Table A-5. These indicators are used to capture the energy deprivation that may affect a person's life. A threshold is predefined and is used for comparing the overall energy deprivations faced by a person which if exceeds the threshold, the person is considered as energy poor. MEPI also allows the weightage of its indicators to change.

Sustainable Energy Development Index (SEDI)

This index was developed by Iddrisu and Bhattacharyya (2015) and consisted of five dimensions and 11 indicators as shown in Appendix Table A-6. This index is used to give scores to the countries based on their performance in the given indicators. The comparison between countries can easily be done by comparing their respective scores. The study of individual dimensions done under SEDI identifies policy paths to improve respective dimensions, while the overall assessment may provide a false sense of achievement to some countries.

Energy Trilemma Index

This tool is used to rank countries based on three dimensions: Energy security, energy equity and environmental sustainability shown in Appendix Table A-7 (WEC, 2015). It also rates the political, societal and economic strengths of countries. In 2016, WEC produced a revised methodology which also included the dimension of country context (WEC, 2016). The main goals of energy trilemma index are: 0

1. Transforming energy supply
2. Advancing energy access
3. Enabling consumer affordability and industry competitiveness
4. Improving energy efficiency and managing demand
5. Decarbonizing the energy sector

Each framework and index reviewed above was developed to measure the level of sustainability in the energy sector, with some strengths and limitations. Some indicators have not provided a clear picture of the main issues or did not capture all dimensions of sustainability, while some indices have more focus in one sub-sector or the individual country. So, based on the strengths and weaknesses of above-mentioned tools, this article attempts to develop a more comprehensive set of indicators signifying energy sustainability.

A Proposed Framework for Measuring the Sustainability of Energy Systems

This study proposes a simple but comprehensive framework "Sustainability of Energy Systems (SES)" to overcome the problems discussed in the indices described in Section 2. SES focuses on a multi-dimensional structure and divides energy sustainability into four sectors: Social, environmental, economic and technology sectors. These sectors are further divided into thirteen sub sectors. These sub sectors consist of forty-six indicators. All these sectors, sub sectors and indicators are selected using exploratory tools. SES is also more accessible and transparent due to its focus on indicators that are globally reportable, have easy access to required data and can be quantified. SES also includes indicators for both energy systems and energy policies and provides a way to quantify all indicators. SES is designed to work for cities, states, provinces and countries. Table 1 explains the sectors, sub-sectors and indicators relating to the sub-sectors for measuring the sustainability level of energy systems.

Selection of Sectors, Sub sectors and Indicators

Studies have recommended a number of indicators for measuring sustainability of the energy systems, however methodologies for selecting the relevant indicators have not been explained sufficiently (Carrera and Mack, 2010; Kemmler and Spreng, 2007). In the process of developing an index, it is important to recognize the problems that are causing sustainability issues in the energy sector. Then the relevant indicators are collected to form a framework. These indicators are not simply the data sets or statistics, instead they provide a deeper understanding of the major issues. The quality of a selected variable depends on how effectively it communicates the problems to the policy makers. Figure 1 shows the methodology used to select the indicators for SES.

The sectors, subsectors and indicators used in this paper for measuring the energy sustainability are

Table 1. Framework for measuring the sustainability of energy systems (SES).

Sub-Sector	Indicators
Economic Sector	
Energy security	• Energy import • Geo-political issues
Energy intensity	• GDP per unit of energy use
Energy conservation & efficiency	• T&D losses • Efficiency of power generation • Energy audits • Energy Conservation and Efficiency targets • Tax credits for energy efficient products • Tax on inefficient cars
Energy usage	• Incentives for using excess electricity • Electricity storage • Promote electricity usage during off-peak hours
Environment Sector	
Climate change	• CO2 intensity of energy mix • CO2 emissions per capita • Carbon taxing • Emissions targets
Protection of natural resources	• Forest area (% of total land) • Electricity production from waste • conHeat production from wastec • Agricultural land (% of total land) • PM2.5 air pollution, means annual exposure (micrograms per cubic meter) • Natural gas reserves to production ratio • Crude oil reserves to production ratio
Renewable energy	• Share of RE (without hydro) • Share of Hydro
Energy safety	• Percentage of the population having access to clean cooking technologies • Safety precaution for nuclear energy
Social sector	
Energy accessibility	• National electrification rate • Population without electricity access • Electricity consumption per capita • Plan & framework for electrification • Quality of electricity supply
Energy affordability	• Average electricity prices for household • Distribution of income (GINI index) • Percentage of monthly household consumption share on housing, water, electricity, gas etc. • Low rates for small consumers
Technology sector	
Clean energy technologies	• Large Scale carbon capture & storage facilities • % of electricity generation by clean energy technologies i.e. solar thermal, Biofuels and Geothermal • Share of EVs • Share of NGVs as % of total NGV Pop. • Use of alternative fuels (CNG, LNG, LPG)
Innovative energy technologies	• Demand side management • Net metering • HVDC transmission • Electricity markets
National standards	• MEPS for buildings and household products • Labels for commercial and public buildings • Labels for household products • Energy labels for cars

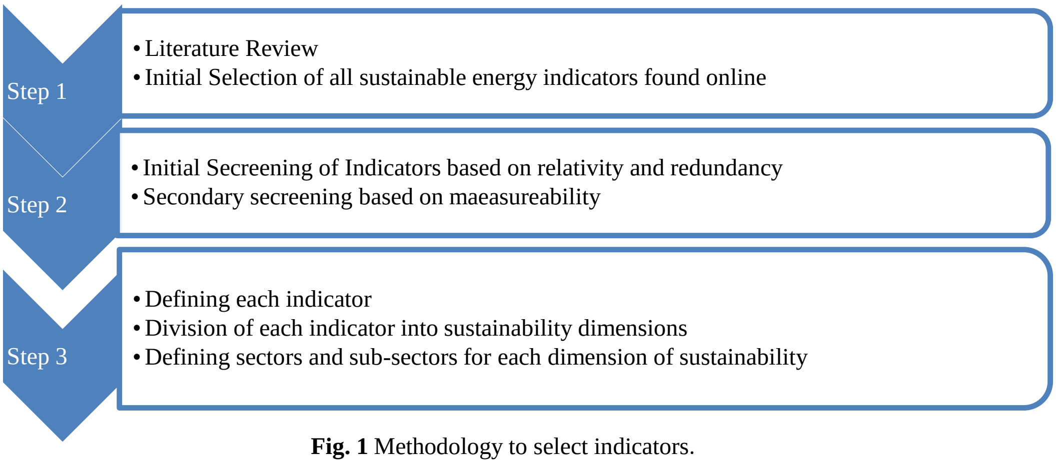

Fig. 1 Methodology to select indicators.

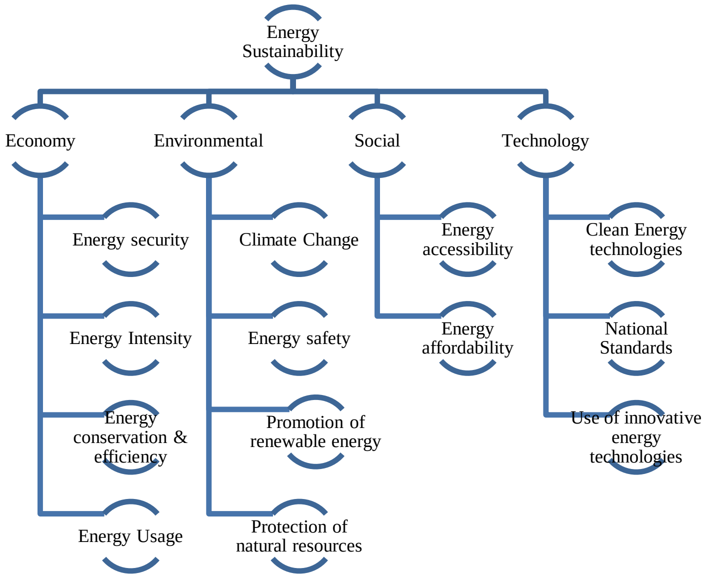

Fig. 2 Sectors and sub sectors of energy sustainability system (SES).

selected in several steps. At first step, literature review helped to find the important sectors relating to energy sustainability. Secondly, the sectors and sub-sectors were selected. To measure sustainability of each sub sector, energy sustainability indicators were identified. Then indicators were defined into two classes: One which is quantifiable and measures sustainability of the energy system, second which is not quantifiable and measures the sustainability of policy measures taken in a country.

Since energy sustainability should improve the economic, social and environmental conditions of a country, supported by technological advancements. Motivated by those theoretical underpinnings, this framework divides energy sustainability into four sectors, namely economic, environmental, social and technological (Fig. 2). These sectors are further divided into thirteen sub-sectors, which are further explained by forty-six indicators. All these sectors, sub sectors and indicators are selected by using exploratory tools for literature review (IAEA, 2005; Jacobson and Delucchi, 2009; Kemmler and Spreng, 2007; Singh et al., 2009).

Criteria for Evaluating the Indicators

After assigning indicators to each sub-sector, sustainability of energy sectors of different countries could be compared. Owing to the complexity of the issue, it is difficult to measure sustainability using simple techniques and indicators. A good set of indicators might create a balance between ease of use and complexity. Sectors, sub sectors and indicators chosen in this paper, provide a good start for a developing country like Pakistan to measure sustainability of its energy sector in comparison with the developed states like USA and EU. These indicators are assigned values between 1 and 0 based on the performance of each country in accordance with the respective indicators. A score of 1 represents full sustainability while 0 represents no sustainability. In case of quantified indicators, a value between 0 and 1 can also be assigned giving us the indication whether the country is on right track or not while in the case of policy indicators only a score of 1. 0.5 over 0 is assigned. If the defined policy measure is adopted by the country, a score of 1 is allotted and 0 is assigned if that policy measure does not exist in that country. A score of 0.5 means, either the policy measure is underway, or it is present in some areas of the respective country.

Countries are ranked based on their scores in the sectors, subsectors and individual indicators. Such a detailed comparison could help the decision makers to easily locate problems relating to the sustainability of the energy sector. This framework can also be used to compare the current sustainability level of a country with the past to see if the country is moving in the right direction.

A notable thing is that some of the indicators selected in this framework cannot be measured using same scale. For example, in the case of some indicators higher value means more sustainability like increased forestation rate, electrification rate, access to clean cooking technologies, while other indicators represent sustainability, if the value is low like energy intensity, CO_2 intensity of energy mix etc. So, to do the scoring, we have adopted the normalization process used by UNDP for the calculation of HDI (Human Development Index). Eq. 1 is used when the higher value of an indicator is indicating sustainability whereas Eq. 2 is used when the lower value of an indicator represents sustainability.

$$V = \frac{V_{Act}-V_{Min}}{V_{Max}-V_{Min}} \qquad Eq.\ 1$$

$$V = \frac{V_{Max}-V_{Act}}{V_{Max}-V_{Min}} \qquad Eq.\ 2$$

Where V is the score of the indicator, V_{Act} represents actual value of the indicator, V_{Max} is the maximum value of the indicator and V_{Min} is the minimum value of the indicator.

Application of the Proposed Framework: Comparing Energy Sustainability in Pakistan, USA and the EU

To get an oversight of the energy sector of Pakistan, this paper compares sustainability in energy sector of Pakistan with those in the EU and USA. The data used here ranges from 2014 to 2018, because most of the data was available for these years (World Bank, 2018a; IEA, 2018b; EEA, 2018b; Enerdata, 2018; WEC, 2018; EC, 2018c; EPA, 2018a; EIA, 2018; EC, 2018b; EPA, 2018b). Table 2 explains the results of comparative analysis between Pakistan, USA and the EU.

Results and Discussion

To find out the inadequacies in the energy sector of Pakistan, a comparative analysis of energy sustainability was conducted between Pakistan, USA and the EU by using our proposed SES framework. Figures 3 and 4 give a clear view of the sectors in which government of Pakistan needs to improve.

Pakistan scored lowest in the sub-sector of electricity accessibility because 50.91 million citizens are still deprived of electricity. This is the case with most developing countries where most of the rural population are still using biomass to fulfil their energy needs. Use of these traditional technologies causes indoor air pollution and results in deforestation. While developed countries like EU and USA have electricity accessibility rate of 100%, the deforestation rate there is very low, and they have huge areas under forests, while Pakistan has alarmingly low levels of forest areas. Government of Pakistan needs to connect its rural areas with the grid so that rural population could also enjoy the benefits of reliable and modern energy services which will also help in the reduction of deforestation rate. Since, Pakistan is being compared with the developed regions, it has scored 0 in this sector, whereas if another developing country with lower accessibility rate was included, the score of Pakistan could have increased. So, scoring might change with the inclusion or exclusion of countries. USA has the highest score for energy security on imported

energy, absence of geo-political issues and huge because of its diverse energy mix, less dependence strategic reserves in case of emergency.

While Pakistan and EU are quite behind in this

sector, mainly because of high dependence on imported energy and presence of geo-political issues. Europe imports large portion of gas from Russia which has threatened to shut down the gas supply to Europe due to different security and regional disputes between Russia and some East-European states (Withnall, 2015). This makes EU to depend on Russia for energy, making its energy system less sustainable. While Pakistan initiated a project to import gas from Iran and after 20 years the project is still incomplete because of regional political instability (The News, 2018). So, the presence of geo-political issues could have a deep impact on the energy security of a country. Pakistan is also far behind in energy conservation and efficiency as compared to USA and the EU. Main reasons include high transmission and distribution losses, absence of mandatory energy labelling and

Table 2. Results of comparative analysis between Pakistan, USA and the EU.

Indicator	EU	USA	Pakistan	Data reference
Energy Security				
Energy import	0	1	0.62	(WorldBank, 2018b)
Geo-political issues	0	1	0	(WorldBank, 2018b)
Energy Intensity				
GDP per unit of energy use	1	0	0.35	(WorldBank, 2018b)
Energy Conservation & Efficiency				
Transmission & distribution losses	0.95	1	0	(WorldBank, 2018b)
Efficiency of electricity generation	0.1	0	1	(Enerdata, 2018)
Energy audits	1	0	0	(WEC, 2018)
Energy conservation & efficiency targets	1	1	1	(WEC, 2018)
Tax credits for energy efficient products	1	1	0	(WEC, 2018)
Tax on inefficient cars	1	1	0	(WEC, 2018)
Energy Usage				
Electricity storage	1	0.50	0	(EC, 2018a, EPA, 2018a)
Incentives for using excess electricity	1	0	0	(WEC, 2018)
Promote electricity usage in off-peak hours	1	1	1	(WEC, 2018)
Climate Change				
CO2 intensity of energy mix	0.36	0	1	(WorldBank, 2018b)
CO2 emissions per capita	0.66	0	1	(WorldBank, 2018b)
Carbon taxing	1	0	0	(EC, 2018a, EPA, 2018a)
Emission targets	1	1	1	(EPA, 2018a, EC, 2018b, GOP 2007)
Renewable Energy				
Share of RE (without hydro)	0.93	1	0	(WorldBank, 2018b)
Share of Hydro	0.07	0	1	(WorldBank, 2018b)
Protection of natural resources				
Forest area (% of land)	1	0.88	0	(WorldBank, 2018b)
Electricity production from waste	1	0.75	0	(IEA, 2018b)
Heat produced from waste	1	0.07	0	(IEA, 2018b)
Agricultural land (% of land area)	0	0.23	1	(WorldBank, 2018b)
PM2.5 air pollution, means annual exposure (micrograms per cubic meter)	0.92	1	0	(WorldBank, 2018b)
Natural gas reserves to production ratio	1	0	0.33	(WEC, 2018) (WorldBank, 2018b)
Oil reserves to production ratio	1	0.9	0	(WEC, 2018) (WorldBank, 2018b)
Energy safety				
Percentage of population having access to clean cooking technologies	0.92	1	0	(WorldBank, 2018b)
Safety precautions for nuclear energy	1	1	1	(WEC, 2018)
Electricity accessibility				
National Electrification Rate	1	1	0	(IEA, 2018a)
Population without electricity access	1	1	0	(IEA, 2018a)
Quality of electricity supply	0.93	1	0	(WorldBank, 2018b)
Plan & Framework for electrification	1	1	0	(SEforAl,l 2018)
Electricity consumption per capita	0.434	1	0	(WorldBank, 2018b)
Electricity affordability				
Distribution of family income (GINI index)	1	0	0.97	(WorldBank, 2018b)
Average electricity prices for household (US cents/kwh)	0	0.7	1	(WorldBank, 2018b) (EEA, 2018a)
Percentage of monthly household consumption share on housing, water, electricity, gas etc.	0.38	0	1	(WEC, 2018) (WorldBank, 2018b) (EEA, 2018a)
Low rates for small consumers	1	1	1	(WEC, 2018)
Large Scale carbon capture & storage facilities	0	1	0	(GCCSI, 2018)
NGVs as % of total NGV Pop.	0.59	0	1	(NGVGLOBAL, 2018)
% of electricity generation by clean energy technologies i.e solar thermal, Biofuels and Geothermal	1	0.37	0	(IEA, 2018a)
Share of electric vehicles	1	0.74	0	(EEA, 2018a)
Promotion of alternative fuels (CNG, LNG, LPG)	1	1	1	(EPA, 2018b)
National standards				
Labels for commercial and public buildings	1	0.5	0.5	(WEC, 2018)
Labels for household appliances	1	1	0.5	(WEC, 2018)
Energy labels for cars	1	1	0	(WEC, 2018)
MEPS for buildings and household products	1	0.5	0.5	(WEC, 2018)
Innovative energy technologies				
Demand side management	1	1	0	(EPA, 2018b, EC, 2018a)
Net marketing	1	1	0.5	(EC, 2018a)
Electricity market	1	0.5	0	(EPA, 2018b)
HVDC transmission lines	1	1	1	WEC, 2018) (EC, 2018a), (EPA, 2018b)

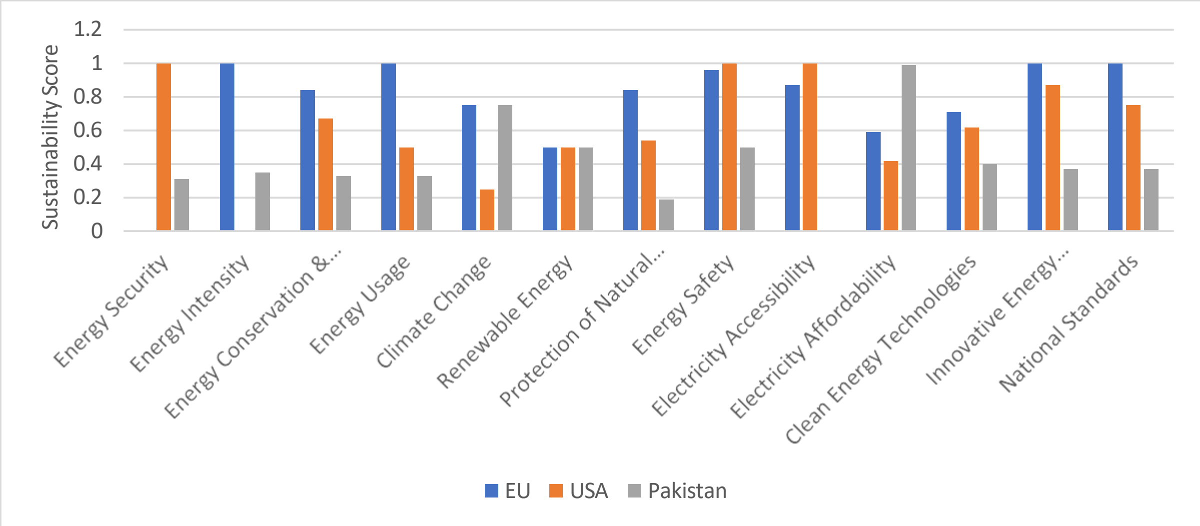

Fig. 3 Results-1.

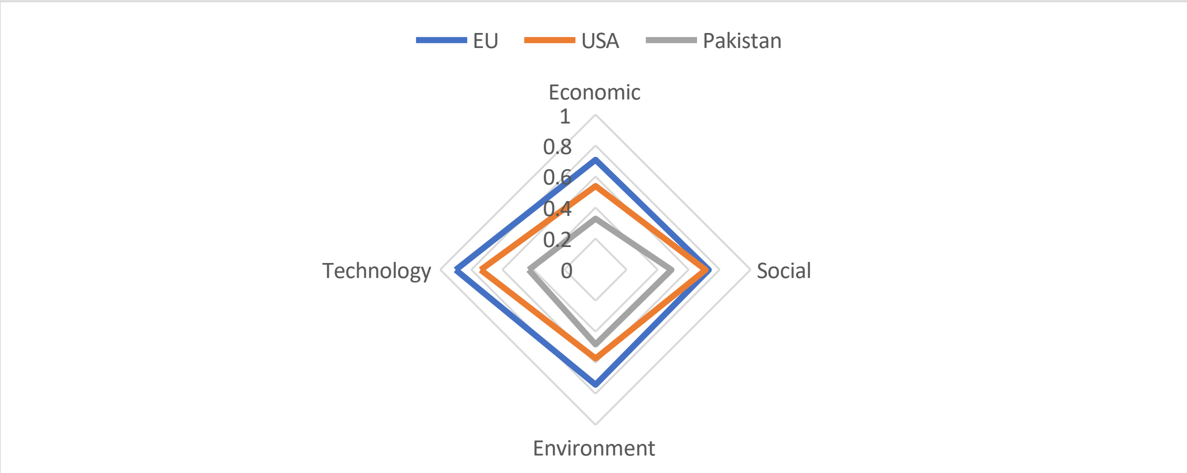

Fig. 4 Results-2.

MEPS and no incentives for using efficient household products and vehicles, while the EU has the highest score because it has the highest percentage of hybrid and electric vehicles. The EU also have less energy intensity as compared to Pakistan and USA. Another important point is that Pakistan is not producing a single megawatt of electricity from solid waste while in EU and USA, significant amount of electricity and heat is produced using municipal solid waste.

Due to increasing dangers of climate change, use of clean energy technologies has become evident. Technologies like clean coal, alternative fuels, co-generation, carbon capturing etc. have gained importance. Like many developing countries, Pakistan also lacks advanced and innovative technologies. Many technologies favoring demand side management and electricity markets are not present in Pakistan. While net metering is not very popular in the country. So, the absence of modern energy services and huge percentage of thermal energy in energy mix makes energy sector of Pakistan less sustainable.

Pakistan has low intensity of carbon emissions and has set targets to further reduce its carbon emissions. But no carbon taxing is found in Pakistan as well as in USA. Pakistan is producing huge amount of energy from hydro, but energy from renewable sources like solar, wind etc. is very low. While no specific subsides are given by Pakistan in the renewable energy sector. The EU and USA are giving huge incentives to the concentration of renewable energy in their energy mix. A deep study of SESFMES could help in discovering the shortcomings of energy systems and policies of developing countries in comparison with the developed states.

Conclusion

A secure, efficient and environment-friendly supply of energy has become mandatory for sustainable development. Sustainable energy systems could help in improving social, environmental and economic conditions of under-developed countries like Pakistan. The main challenges for ensuring sustainable energy are universal access of affordable, reliable and modern energy services. The current energy system of Pakistan is not sustainable because of high dependence on fossil fuels, imported energy, inefficient transmission and distribution system, low electrification rate, absence of modern and clean energy technologies and increasing environmental degradation. However, research to measure overall sustainability of the energy system of Pakistan by using a systematic approach is lacking.

This paper by building upon previous indices and frameworks has proposed a framework “Sustainable Energy System” for measuring sustainability level of energy systems. SES is a comprehensive framework and has included economic, social, environmental and technological dimensions with thirteen sub-dimensions and forty-nine indicators representing sustainability of the energy systems. Use of this tool has the potential to highlight the key energy sector issues and provide new insights to the policy makers for improving energy sustainability in the developing countries. Later, the framework has been applied to measure sustainability in the energy system of Pakistan in comparison to the EU and the USA energy systems. The reason to compare with the developed nations was to see where Pakistan stands in comparison to the best performing nations on sustainability front. It is evident from the comparative analysis that Pakistan has performed poorly on various fronts of energy sustainability. The European Union has performed well in all aspects of energy sustainability including economic, environmental, social and technological, followed by the US and then Pakistan. On a sustainability index of 0-1, Pakistan has obtained the score between 0.2-0.4, the USA between 0.4-0.6 and the EU in the range of 0.6 to 0.8.

Scoring low on the SES index can have significant implications for Pakistan. High energy intensity and transmission and distribution losses raise production costs that can affect the competitiveness of export industries. Deforestation and unsustainable extraction and use of fossil fuels can lead to ecosystem degradation and loss of biodiversity. Lower energy accessibility and high energy costs can result in a portion of the population staying energy-poor for the long term which can cause income inequality, poverty, and discrimination. Pakistan is also lagging in terms of the use of innovative energy technologies. This can result in higher dependency on imported fossil fuels and a loss of opportunity to create a green energy market and compete globally.

This paper suggests that Pakistan needs to take some important policy decisions to increase the sustainability of its energy system. The key areas that require improvement on the sustainability fronts include energy security, energy efficiency and conservation, accessibility to clean energy resources/electricity, clean energy technologies/renewable energy, innovative energy technologies such as net-metering, energy markets, etc. and last but not the least, the protection of its natural energy resources. These improvements can be achieved by redefining energy conservation and efficiency target and inclusion of roadmap on how to implement them. Rural electrification programs should be included in Energy policy to provide cheaper energy options like anaerobic digesters to communities that do not have access to electricity and clean cooking technologies. Creation of national clean energy innovation funds can also help in improving the existing technologies

This framework can also be applied and extended to more indicators and countries for a comparative analysis of sustainable energy systems, provided sufficient and reliable data is available on all the indicators. In future works, a global index of sustainable energy systems across the developed and developing countries, based on an extended version of SES framework can be developed by building on the proposed framework. This would help the policymakers, businesses and international organizations for better policy interventions aimed at enhancing sustainable development at the scoring low on the SES index can have significant implications for Pakistan. High energy intensity and transmission and distribution losses raise production costs that can affect the competitiveness of export industries. Deforestation and unsustainable extraction and use of fossil fuels can lead to ecosystem degradation and loss of biodiversity. Lower energy accessibility and high energy costs can result in a portion of the population staying energy-poor for the long term which can cause income inequality, poverty, and discrimination. Pakistan is also lagging in terms of the use of innovative energy technologies. This can result in higher dependency on imported fossil fuels and a loss of opportunity to create a green energy market and compete globally.

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Declarations

Funding: No funding

Conflicts of interest/Competing interests (include appropriate disclosures): No conflict of interest exists

Availability of data and material (data transparency): Data can be provided if required

Code availability (software application or custom code): NA

Authors' contributions (optional: please review the submission guidelines from the journal whether statements are mandatory): Authors contribute equally

References

Ali, M., Wazir, R., Imran, K., Ullah, K., Janjua, A. K., Ulasyar, A., Guerrero, J. M. (2021). Techno-economic assessment and sustainability impact of hybrid energy systems in Gilgit-Baltistan, Pakistan. *Energy Reports*. ***7***, 2546-2562.

Carrera, D. G., Mck, A. (2010). Sustainability assessment of energy technologies via social indicators: Results of a survey among European energy experts. *Energy policy*, **38** (2), 1030-1039.

Chu, S., Majumdar, A. (2012). Opportunities and challenges for a sustainable energy future. *Nature* **488** (7411), 294.

EC (2018a). Energy. European Comission, accessed 4-10-2018. https://ec.europa.eu/energy/.

EC (2018b). EU Emissions trading system (EU ETS). European Comission, accessed 4-10-2018. https://ec.europa.eu/clima/policies/ets_en.

EC (2018c). Study on regulatory incentives for investments in electricity and gas infrastructure projects. European Comission, accessed 4-10-2018.https://ec.europa.eu/commission/index_en.

EEA (2018a). Data and maps. European Environment Agency, accessed 2-10-2018. https://www.eea.europa.eu/data-and-maps/.

EEA (2018b). Electric vehicles as a proportion of the total fleet. european environment agency, accessed2-10-2018. https://www.eea.europa.eu/data-and-maps/indicators/proportion-of-vehicle-fleet-meeting-4/assessment-2.

EIA (2018). Direct federal financial interventions and subsidies in energy in Fiscal Year 2016. United States Energy Information Administration, accessed 4-10-2018. https://www.eia.gov/analysis/requests/subsidy/.

Emodi, N. V., Kyung, J. (2015). Sustainable energy development in Nigeria: Current status and policy options. *Renewable and Sustainable Energy Reviews,* **51**, 356-381.

EPA (2018a). Energy and environment. United States Environment Protection Agency, accessed4-10-2018. https://www.epa.gov/energy/electricity-storage.

EPA (2018b). U.S. Electricity grid and markets. United States Environment Protection Agency. https://www.epa.gov/greenpower/us-electricity-grid-markets.

Evans, A., Strezov, V., Evans, J. T. (2009). Assessment of sustainability indicators for renewable energy technologies. *Renewable and sustainable energy reviews*, **13** (5), 1082-1088.

Glavič, P., Lukman, K. R. (2007). Review of sustainability terms and their definitions. *Journal of Cleaner Production*, **15** (18), 1875-1885.

Goldemberg, J. (2007). Ethanol for a sustainable energy future. *Science*, **315** (5813), 808-810.

Hussain, A., Perwez, U., Ullah, K., Kim, C. H., Asghar, N. (2021). Long-term scenario pathways to assess the potential of best available technologies and cost reduction of avoided carbon emissions in an existing 100% renewable regional power system: A case study of Gilgit-Baltistan (GB), Pakistan. *Energy*, ***221***, 119855.

IAEA (2005). Energy indicators for sustainable development: Guidelines and methodologies. Austria.

Iddrisu, I., Bhattacharyya, C. S. (2015). Sustainable energy development index: A multi-dimensional indicator for measuring sustainable energy development. *Renewable and Sustainable Energy Reviews*, **50** 513-530. doi: 10.1016/j.rser.2015.05.032.

IEA (2018a). Energy access database. International Energy Agency, accessed 12-10-2018. https://www.iea.org/energyaccess/database/.

IEA (2018b). Energy statistics. International Energy Agency, accessed 1-10-2018. https://www.iea.org/statistics/?country=WORLD&year=2015&category=Key%20indicators&indicator=TPESbySource&mode=chart&categoryBrowse=false.

IEA (2018c). World energy outlook. International Energy Agency, accessed 10-11-2018. https://www.iea.org/weo/.

Jacobson, M. Z., Delucchi, M. A. (2009). A path to sustainable energy by 2030. *Scientific American*, **301** (5), 58-65.

Johansson, T. B., Anand, P., Nekicenovic, N., Echeverri, G. L. (2012). Global energy assessment: toward a sustainable future: Cambridge University Press.

Kemmler, A., Daniel, S. (2007). Energy indicators for tracking sustainability in developing countries. *Energy policy*, **35** (4), 2466-2480.

Mainali; B., Pachauri, S., Rao, N., Semida, S. (2014). Assessing rural energy sustainability in developing countries. *Energy for Sustainable Development*, **19**, 15-28.

Neves, A. R., Vítor, L. (2010). Energy sustainability indicators for local energy planning: Review of current practices and derivation of a new framework. *Renewable and Sustainable Energy Reviews*, **14** (9) 2723-2735. doi: 10.1016/j.rser.2010.07.067.

Nussbaumer, P., Morgan, B., Modi, V. (2012). Measuring energy poverty: Focusing on what matters. *Renewable and Sustainable Energy Reviews*, **16** (1), 231-243. doi: 10.1016/j.rser.2011.07.150.

Office Human Development Report (2016).

OLADE, ECLAC, GTZ. (2000). Energy and sustainabale development in Latin America and the Caribbean: Guide for policymaking.

Oyedepo, S. O. (2012). On energy for sustainable development in Nigeria. *Renewable and sustainable energy reviews*, **16** (5), 2583-2598.

Ozturk, M., Yuksel, E. Y. (2016). Energy structure of Turkey for sustainable development. *Renewable and Sustainable Energy Reviews*, **53**, 1259-1272.

Shortall, R., Brynhildur, D. (2017). How to measure national energy sustainability performance: An Icelandic case-study. *Energy for Sustainable Development*, **39**, 29-47.

Singh, R. K., Murty, H. R., Gupta, S. K., Dikshit, A., K. (2009). An overview of sustainability assessment methodologies. *Ecological indicators*, **9** (2), 189-212.

The News. (2018). PTI govt committed to implement Iran-Pakistan gas pipeline project. The News, accessed 8-10-2018. https://www.thenews.com.pk/print/367676-pti-govt-committed-to-implement-iran-pakistan-gas-pipeline-project.

UN (2018). Sustainable development goals. United Nations, accessed 2-10-2018. https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

Vidadili, N., Suleymanov, E., Bulut, C., Mahmudlu, C. (2017). Transition to renewable energy and sustainable energy development in Azerbaijan. *Renewable and Sustainable Energy Reviews*, **80**, 1153-1161.

WEC (2015). Energy trilemma index. World Energy Council, accessed 10-11-2018. https://www.worldenergy.org/data/trilemma-index/country/switzerland/.

WEC (2016). World energy trilemma. Defining measures to accelerate the energy transition. World Energy Council, accessed 10-11-2018. https://www.worldenergy.org/publications/2016/world-energy-trilemma-2016-defining-measures-to-accelerate-the-energy-transition/.

WEC (2018). Energy efficiency policies and measures. World Energy Council, accessed 14-06-2018. https://www.worldenergy.org/data/energy-efficiency-policies-and-measures/.

WEF (2017). Global energy architecture performance index 2017. World Economic Forum.

Withnall, A. (2015). Putin's gas threat: What happens if Russia cuts the gas to Europe?. Independent, accessed 8-10-2018. https://www.independent.co.uk/news/world/europe/putins-gas-threat-what-happens-if-russia-cuts-the-gas-to-europe-10074294.html.

World Bank. (2018a). The World Bank Report.

Appendix

Table A-2. Energy development index.

Dimensions	Indicators	Strengths	Weaknesses
Social, Economic and Environmental	➢ Per capita consumption of commercial energy ➢ Per capita electricity consumption in residential sector ➢ Contribution of modern fuels in the total consumption of residential sector ➢ Percentage of population with electricity access	➢ Multidimensional indicator ➢ Provide medium to long term projections ➢ Includes many scenarios for projections including new policies scenario, sustainable development scenario and current policies scenario	➢ Measures indicators only at consumption stage ➢ Not comparing demand with the supply side ➢ No information about countries' transitions towards sustainability

Table A-3. Energy sustainability indicators.

Dimensions	Indicators	Strengths	Weaknesses
Economic, natural resources and social	➢ Energy autarky ➢ Reliability in face of external changes ➢ Productivity of Energy ➢ Coverage of Electric power ➢ Basic energy needs coverage ➢ Relative purity of energy use ➢ Use of renewables ➢ Scope of fossil fuel resources	➢ Provides key factors to formulate energy policy ➢ Useful to study about how the energy sector has worked during a specific period	➢ Doesn't include geo-political issues ➢ Doesn't calculate aggregate index ➢ Study was applied only to Latin America and Caribbean countries

Table A-1. Energy indicators for sustainable development.

Dimensions	Indicators	Strengths	Weaknesses
Social, economic and environmental	➢ Population without access to electricity or commercial energy, or highly dependent on non-commercial energy ➢ Percentage of household income spent on electricity and fuel ➢ Household energy use for each income group and corresponding fuel mix ➢ Accident fatalities per energy produced by fuel chain ➢ Energy use per Capita ➢ Energy use per unit of GDP ➢ Efficiency of energy conversion and distribution ➢ Reserves-to production Ratio	➢ Large number of indicators provides a comprehensive information about sustainability in a country ➢ Provides complete description of all indicators ➢ Provide a consistent set of energy indicators applicable worldwide	➢ Very difficult to obtain data of countries in accordance with the said indicators ➢ Some indicators of sustainable development contain errors in the aggregation process due to nonuniform definition of indicator scales. ➢ Some indicators provide ambiguous information

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Dimensions	Indicators	Strengths	Weaknesses
	➢ Intensity of industrial energy ➢ Intensity of agricultural energy ➢ Intensity of commercial energy ➢ Intensity of household energy ➢ Intensity of transport energy ➢ Fuel shares in energy and electricity ➢ Percentage of non-carbon energy in energy and electricity ➢ Percentage of renewables in energy and electricity ➢ Energy prices by fuel to end-users and by sector ➢ Dependency on net energy import ➢ Stocks of critical fuels per corresponding fuel consumption ➢ GHG emissions from energy production and use per capita and per unit of GDP ➢ Ambient concentrations of air pollutants in urban areas ➢ Air pollutant emissions from energy systems ➢ Contaminant discharges in liquid effluents from energy systems including oil discharges ➢ Soil area where acidification exceeds critical load ➢ Deforestation rate credited to energy use ➢ Ratio of solid waste generation to units of energy produced ➢ Ratio of solid waste properly disposed of to total generated solid waste ➢ Ratio of solid radioactive waste to units of energy produced ➢ Ratio of solid radioactive waste awaiting disposal to total generated solid radioactive waste		

Table A-4. Energy architecture performance index.

Dimensions	Indicators	Strengths	Weaknesses
Economic growth and development, environmental sustainability and energy access and security	➢ GDP per unit of energy use/energy intensity ➢ Energy imports cost ➢ Value of energy exports ➢ Extent of artificial alteration to pricing of gasoline ➢ Extent of artificial ➢ alteration to pricing of diesel ➢ Electricity prices for electricity ➢ Alternative and nuclear energy	➢ Provides latest available global energy data ➢ Provides strengths and target areas for improvement of energy systems	➢ Doesn't include technology dimension ➢ Doesn't include important indicators ➢ for environment sustainability like deforestation rate, carbon taxing, carbon capture and

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Dimensions	Indicators	Strengths	Weaknesses
	➢ alteration to pricing of diesel ➢ Electricity prices for electricity ➢ Alternative and nuclear energy ➢ CO2 emissions caused by production of electricity ➢ Energy sector methane emissions ➢ Energy sector Nitrous oxide emissions ➢ PM2.5, country level ➢ Average fuel economy for passenger cars ➢ Electrification rate ➢ Electric supply quality ➢ Share of population dependent on solid fuels for cooking ➢ Diversity of total primary energy supply ➢ Dependence on energy import ➢ Diversification of import counterparts		important indicators for environment sustainability like deforestation rate, carbon taxing, carbon capture and storage etc. ➢ Energy conservation and efficiency indicators like MEPS, energy labelling, hybrid vehicles etc. are not included

Table A-6. Multidimensional energy poverty index (MEPI).

Dimensions	Indicators	Strengths	Weaknesses
Household consumption including cooking, lighting, appliances, entertainment/ education and communicatio n	➢ Cooking fuel types ➢ Food cooked on stove or open fire (no hood/chimney) if using any fuel beside LPG, electricity, natural gas, or biogas ➢ Electricity access ➢ Access to fridge ➢ Access to radio or tv ➢ Access to phone	➢ provides a multidimensional approach towards energy poverty ➢ Quantify energy poverty ➢ Allows to change the weightage of indicators	➢ Doesn’t include energy sustainability ➢ Scope is limited to household needs

Table A-6. Sustainable energy development index.

Dimensions	Indicators	Strengths	Weaknesses
Technical, social, environmental, economic and institutional	➢ Percentage of depletable energies in total primary energy supply ➢ Depletion coefficient of local energy resources ➢ Overall system conversion efficiency ➢ Commercial energies per capita consumption ➢ Final energy intensity ➢ Percentage of productive use of energy ➢ Residential sector clean energies consumption per capita ➢ Income inequality ➢ Percentage of dirty fuels	➢ Includes institutional dimension ➢ Comparison between countries could be easily done ➢ Focuses on both intra and inter-generational needs ➢ Has the ability to give forewarning to a country	➢ Not immune to masking effect ➢ A look at the overall SEDI value alone may therefore give a false sense of achievement to some countries ➢ Environmental dimension is missing important indicators like carbon taxing, carbon storage, deforestation etc.

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Dimensions	Indicators	Strengths	Weaknesses
Energy security, energy equity, environmental sustainability and country context	➢ Diversity of primary energy supply ➢ Consumption of energy in relation to GDP growth ➢ Dependence on energy imports ➢ Electricity generation diversity ➢ Energy storage ➢ Preparedness ➢ Access to electricity ➢ Access to clean cooking ➢ Quality of electricity supply ➢ Quality of supply in urban vs rural areas ➢ Electricity prices ➢ Gasoline and diesel prices ➢ Natural gas prices ➢ Final energy intensity ➢ Efficiency of power generation and T&D ➢ GHG emission trend ➢ Change in forest area ➢ CO2 intensity ➢ CO2 emission per capita ➢ CO2 from electricity generation ➢ Macroeconomic environment ➢ Effectiveness of government ➢ Political stability ➢ Perception of corruption ➢ Transparency of policy making ➢ Rule of law ➢ Regulatory quality ➢ Intellectual property protection ➢ FDI and technology transfer ➢ Capacity for innovation ➢ Number of patents issues for residents ➢ Foreign direct investment net inflows ➢ Ease of doing business ➢ Waste water treatment ➢ Air pollution		Doesn’t include technology, economic dimension, environmental dimension, carbon capture, storage and carbon taxing